High Resolution Soft X-ray Microscopy

Weilun Chao[1 2 *], Erik H. Anderson[1], Gregory Denbeaux[1], Bruce Harteneck[1], Mark Le Gros[1], Angelic Lucero[1], Deirdre Olynick[1], David Attwood[1 2]

[1] Lawrence Berkeley National Laboratory, Berkeley, CA 94720
[2] University of California at Berkeley, Berkeley, CA 94720

ABSTRACT

The XM-1 is a soft x-ray full-field microscope that uses zone plates for the condenser and objective lenses. One of the main features of XM-1 is the high spatial resolution, which is made possible by the fine features of the objective zone plate. At present, the microscope uses a zone plate with an outer zone width of 25 nm. Several test patterns containing periodic lines and spaces were fabricated to measure the resolution of the microscope. Experimental data shows that the microscope can resolve 25 nm features. As simulations indicate that good contrast can be observed with even smaller features, test patterns with finer features are being fabricated to actually determine the resolution limit of the microscope.

Keywords: x-ray microscope, XM-1, zone plate, resolution

1. INTRODUCTION

The x-ray microscope is an extension of a visible light microscope to the x-ray region. It makes use of the differential absorption of the sample for imaging. The microscope not only provides very high resolution, but also a unique capability to image a thick sample in aqueous environment, which other kinds of high resolution microscopes (like electron microscopes or atomic force microscopes) do not have. X-ray interaction with matter allows the microscope to provide elemental and chemical contrast. All these unique features make this microscope very useful in biology, material science, and other areas[1,2].

At the Advanced Light Source (ALS) of Lawrence Berkeley National Laboratory (LBNL), we have a soft x-ray microscope XM-1 that operates between 250 eV and 900 eV. Our research is to measure the resolution of the system and understand the factors that affect it. In this paper, we will present the latest result of the resolution measurement.

2. SOFT X-RAY MICROSCOPE XM-1

In the full-field soft x-ray microscope XM-1, a plane mirror is illuminated by bending magnet radiation from the ALS (figure 1). The mirror reflects the radiation onto a condenser zone plate (CZP), which in turn focuses the light on the sample plane through a pinhole. The radiation from the sample is then imaged on the CCD by a micro zone plate (MZP). All the focusing is chosen to be performed by diffractive optics because in soft x-ray region the δ of the refraction index for most materials ($n = 1 - \delta + i\beta$) is much less than unity; conventional lenses would have to be very thick to produce the required amount of bending and would absorb most of the radiation.

The combination of the CZP and the pinhole serves as a monochromator to select a particular wavelength for imaging. Selection of the pinhole size is not trivial because of the trade-off between spectral resolution and radiation flux. A set of parameters (figure 1) with pinhole size of 15 um was chosen to give $\lambda/\Delta\lambda \sim 700$ [3], which is sufficient for our applications.

Both zone plates were fabricated in the Nanofabrication Laboratory in the Center for X-ray Optics (CXRO)[4]. As resolution depends on the outer zone width of a zone plate, our goal is to fabricate micro zone plates with the outer zones as small as

[*] Correspondence: Email: wlchao@lbl.gov; Telephone: 510-486-4079; Fax: 510-486-4550.

possible. Currently, using the Nanowriter, we are able to obtain zone plates with 25-nm outer zone width (figure 2). The parameters of the MZP are listed in figure 1.

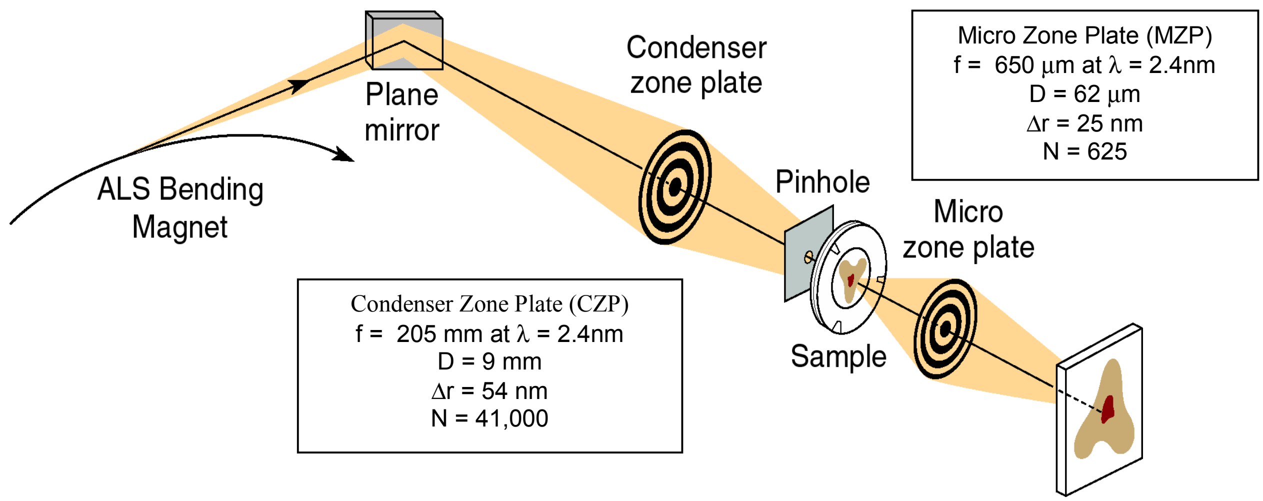

Figure 1. Schematics of the Soft X-ray Microscope XM-1 at beamline 6.1.2 of the Advanced Light Source (ALS). Bending magnet radiation from the ALS is used to illuminate the sample. The degree of partial coherence of the system is 0.45

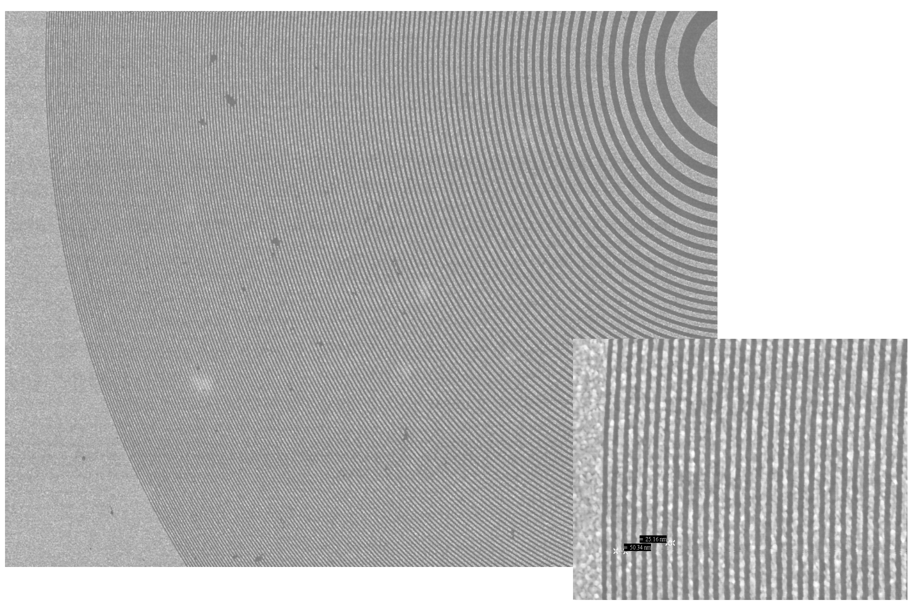

Figure 2. An SEM micrograph of the current 25 nm micro zone plate (MZP). Both the condenser and the micro zone plates are fabricated with the Nanowriter electron beam lithography tool in the Nanofabrication Laboratory. The resolution of the microscope is determined in large part by the outer zone width of the MZP.

3. TEST PATTERNS

Several test objects have been made for measuring the resolution of the system. They consist of lines and spaces with different periods and duty cycles. One of them is shown in figure 3. They were fabricated by the same lithography tool as used for the zone plates. To determine the resolution limit of the system, test patterns with feature sizes as small as the

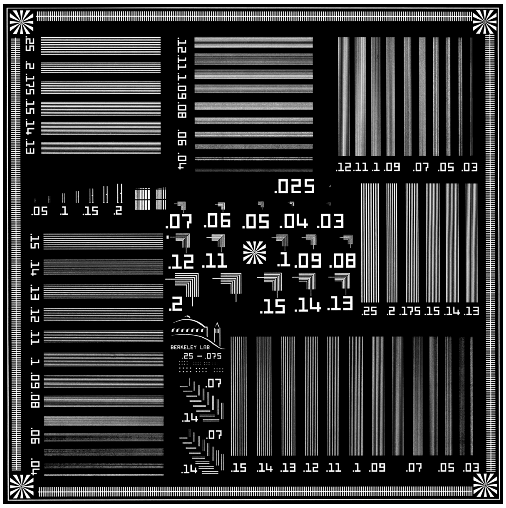

Figure 3. One of the test objects used for resolution measurement. This gold-plated object contains two sets of lines and spaces with linewidths from 30 nm to 250 nm. One set has line-to-space ratio of 1:1, another has the ratio of 1:2. The center of the object has a set of elbows with linewidths as narrow as 25 nm. The dimension of this test object is 120 μm X 120 μm

resolution are needed. The resolution of the microscope is expected to be slightly below the outer zone width of the MZP, depending on the partial coherence of the system. However, the current outer zone width is close to the limit of the fabrication tool. Thus, determination of resolution is not straightforward. Several resists, including Calixarene and HSO, and different fabrication techniques have been experimented for obtaining high quality lines and spaces with small periods[4]. The latest test object, which is one of our best, was made with HSO resist and was plated with nominally 40-nm thick gold. Resist between the lines was not etched away to maintain the quality of the patterns.

4. RESULTS

Our latest test object has recently been imaged under the microscope. Figure 4 shows images of some of the lines and spaces with small periods, along with their corresponding SEM images. Because of the lack of "landmarks" on the object, the x-ray images and SEM images might not be taken from the same location. The x-ray images were taken at wavelength of 2.4 nm with 3100x magnification. The x-ray images have pixel sizes of 8 nm.

The x-ray images clearly shows that the patterns can be resolved by the microscope. The normalized lineout of the 15 nm lines and 35 nm spaces gives us a measured contrast of 24%. Figure 5 shows the experimental contrast as a function of the spatial frequency of the corresponding patterns. The theoretical cutoff of the microscope, which depends on the numerical apertures of the KZP and MZP, is about 17 nm half-period. Along with the assumption that large features would have 100% contrast, the points are fitted with a numerical curve. Lines and spaces with a half-period of 23 nm are predicted to yield 15.3% contrast, which is the Rayleigh criterion.

5. FUTURE WORK

Currently, the Nanofabrication laboratory is upgrading its etching system. The new system will enhance our capability to fabricate test patterns of higher quality with feature size smaller than the expected resolution. To understand the factors that affect the resolution, we will also develop a theoretical model and compare the experimental contrasts with the prediction.

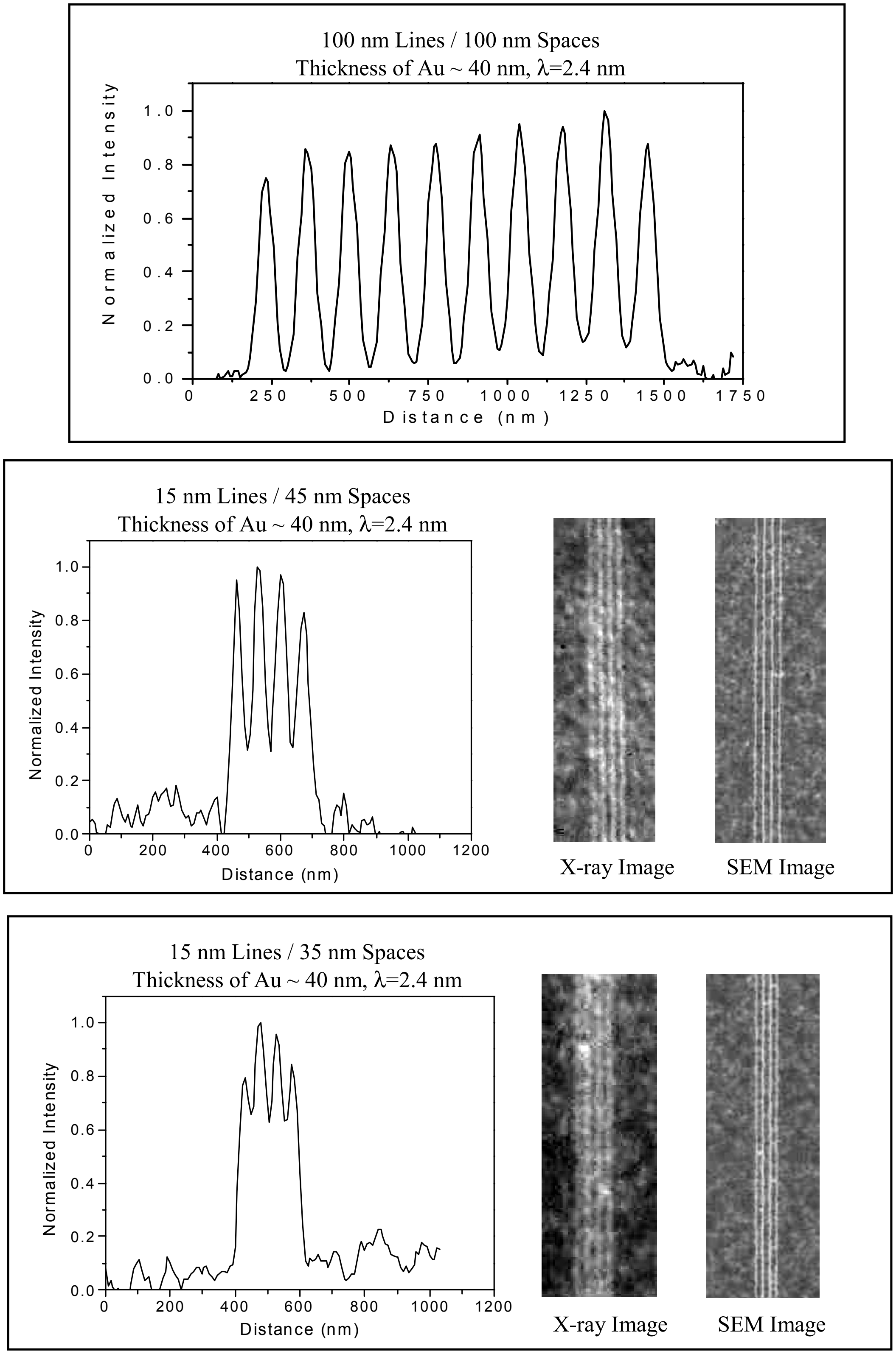

Figure 4. X-ray and SEM images of lines and spaces with different periods. The SEM and X-ray images may not be taken at the same location. Both have the pixel size of 8 nm. The normalized lineout of 15 nm lines and 35 nm spaces has 24% contrast.

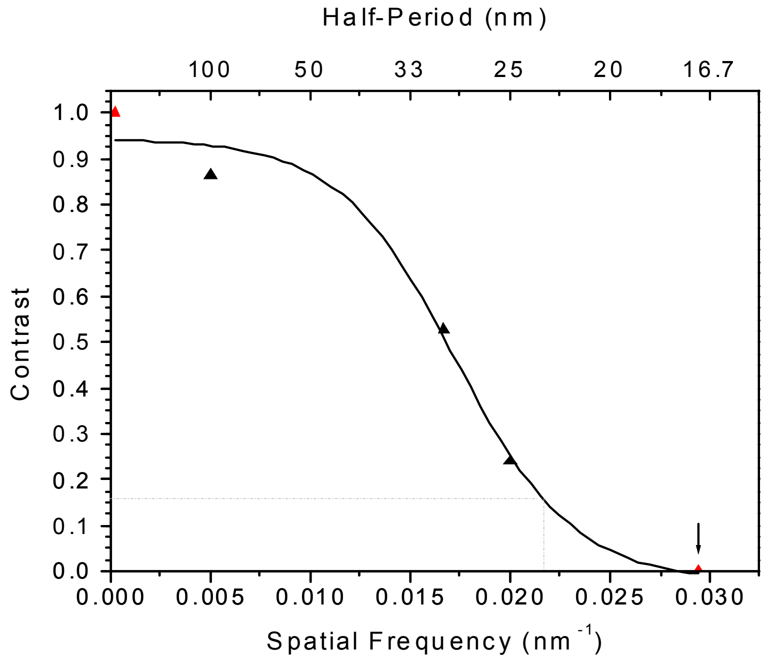

Figure 5. Experimental contrast of different periods. Also shown is the calculated cutoff (half-period of 17 nm) of the microscope. The solid line is a least squares fit to the experimental data, the cutoff, and an assumed value of unity at zero spatial frequency. The Rayleigh criterion of 15.3% contrast corresponds to a half-period of 23 nm.

ACKNOWLEDGEMENTS

The authors would like to thank the Department of Energy's Office of Basic Energy Sciences, DARPA, and the Air Force Office of Scientific Research for their generous support.

REFERENCES

1. G. Denbeaux, E. H. Anderson, W. Chao, T. Eimueller, P. Fischer, L. Johnson, C. Larabell, M. A. LeGros, A. E. Lucero, D. L. Olynick, D. Yager, and D. T. Attwood, Jr., "Applications of soft x-ray microscopy at high-spatial resolution," *Soft X-Ray and EUV Imaging Systems*, SPIE 4146, (2000).
2. A. Lucero, W. Chao, G. Denbeaux, T. Eimuller, P. Fischer, L. Johnson, M. Koehler, C. Larabell, M. Le Gros, D. Yager, and D. Attwood, "XM-1, the high-resolution soft x-ray microscope at the Advanced Light Source," *Soft X-Ray and EUV Imaging Systems*, Edited by W. M. Kaiser and R. H. Stulen, SPIE 4146, (2000).
3. G. Denbeaux, L.E. Johnson, and W. Meyer-Ilse, "Spectroscopy at the XM-1," *X-Ray Microscopy*, Edited by W. Meyer-Ilse, T. Warwick and D. Attwood, AIP, New York, 1999.
4. E. H. Anderson, D. L. Olynick, B. Harteneck, E. Veklerov, G. Denbeaux, W. Chao, A. Lucero, L. Johnson, and D. Attwood Jr., "Nanofabrication and Diffractive Optics For High-Resolution X-Ray Applications," J.Vac. Sci Techn., (2000), to be published.